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Colombian Soil Stabilized with Geopolymers for Low Cost Roads

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Abstract
In some countries, low cost roads have an important role in the road network as they provide a faster way to travel between villages and can improve the access to basic services.
In this paper, a geopolymer synthetized from low calcium fly ash and an alkaline solution made from sodium silicate and sodium hydroxide was used to stabilize a silty sand from Colombia, in order to evaluate its suitability for unpaved roads.
Results show that strength and stiffness are significantly increased by this treatment as measured by unconfined compression strength tests and seismic wave measurements performed on several mixtures. Some existing specifications for soil-cement were also applied in this new stabilized soil and the results revealed a similar behaviour to soil-cement mixtures in terms of resistance to wetting and drying cycles, resistance at early ages and resistance to immersion.

Keywords: geopolymer, fly ash, immersion, seismic wave velocities, unconfined compression strength

1 Introduction

Low cost roads are roads with low levels of traffic, sometimes without bituminous surface layers, where the soil is compacted and shaped into a camber to shed rainwater to each side. However, for many circumstances it is necessary to stabilize or improve the in-situ soils, either with other selected

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soils/aggregates or with binders, building a stronger pavement on top to support heavier vehicles or higher traffic flows. This will help spread vehicle loads without causing deformation.

Traditionally, these binders are cement and/or lime, which bind the soil particles together through chemical reactions. However, cement production has severe environmental impacts, using vast amounts of fossil fuels and being responsible for the emission of more than 5% of all the carbon dioxide worldwide (Provis & Deventer, 2014). Hence, the use of increasing amounts of waste as a material source for the construction industry represents a highly significant contribution for the reduction in cement consumption.

In general terms, alkaline activation is a reaction between alumina-silicate materials and alkali or alkali earth substances, namely alkaline ions like sodium or potassium, or alkaline earth ions like calcium. It can be described as a polycondensation process, in which the silica and alumina units interconnect and share the oxygen ions. Materials formed using reactions between silica and alumina and alkali cations like sodium or potassium are very similar, at a molecular level, with natural rocks, sharing their stiffness, durability and strength (Davidovits, 1991). For soil improvement applications, the alkaline activation of fly ash creates a geopolymeric gel to bind the soil particles as it was successfully applied to replace traditional Portland cement concrete (Bernal, et al., 2011)

However, few works have studied the use of geopolymeric binders in soil improvement applications and none as soil stabilization technique for low cost roads. In previous work (Rios, et al., 2015), the authors have explored few mixtures and very promising results were found namely in terms of its stress-strain behaviour by means of triaxial tests. In this work, a wide range of mixtures were studied and durability tests were performed to evaluate the possible application of this material as a surface layer for an unpaved road.

2 Materials

The soil used in this work is classified as a silty sand (SM) according to the unified classification system (ASTM-D2487, 2006) and it was collected in a site located in the south of Bogotá, Colombia. The fines are non plastic, and the effective diameter (D_{50}) is 0.20 mm. It is a rather well graded soil with uniformity and curvature coefficients of 210 and 8.6 respectively.

Fly ash are very fine residues transported by the smoke generated by coal combustion. The fly ash used in this work is classified as Class F, with a percentage of CaO of less than 10%, and a Portuguese coal-fired thermoelectric power plant produced it.

The alkaline activator solution is composed by sodium silicate (SS) and sodium hydroxide (SH). The SH is prepared dissolving sodium hydroxide flakes in water until the desired concentration is obtained. The sodium silicate solution has a bulk density of 1.464 g/cm^3, a sodium oxide (Na_2O) content of 13.0% and a SiO_2/Na_2O ratio of 2.0. The SH flakes have a specific gravity of 2.13 at 20ºC (99 wt%).

The experimental plan comprised 16 types of mixtures defined according to the fly ash content, the sodium hydroxide concentration and the SS/SH ratio. Two percentages of fly ash were considered: 10% (A series) and 20% (B series) of the dry soil. For each series, four molal concentrations of sodium hydroxide (5, 7.5, 10 and 12.5) and two sodium silicate to sodium hydroxide ratios (SS/SH) of 0.5 and 1.0 were considered. To identify the mixtures, the fly ash percentage is represented by letters A or B, the SS/SH ratio by 05 or 1 and the concentration of sodium hydroxide by C5, C7, C10 or C12, as presented in Table 1. The specimens were compacted in the optimum point of the corresponding Modified Proctor curve obtained in the mixtures of soil and fly ash, for the two fly ash percentages.

Name	SH concentration (molal)	SS/SH (wt)	% Fly ash	Dry unit weight (kN/m^3)	Liquid content (%)
A05C5	5	0.5	10	19.92	8.0
A05C7	7.5				
A05C10	10				
A05C12	12.5				
A1C5	5	1			
A1C7	7.5				
A1C10	10				
A1C12	12.5				
B05C5	5	0.5	20	19.53	8.8
B05C7	7.5				
B05C10	10				
B05C12	12.5				
B1C5	5	1			
B1C7	7.5				
B1C10	10				
B1C12	12.5				

Table 1. Mixtures composition

3 Testing Procedures

The mixtures were prepared by adding the necessary quantities of soil, fly ash and the alkaline activator. First the SH flakes were dissolved in water until the required concentration and when cooled down, added to the sodium silicate solution. The soil and fly ash were mixed until complete homogenization and then the alkaline solution was added gradually to the solids and mixed manually. The mixture was statically compacted inside a stainless steel mould with 142 mm of height and 71 mm of diameter, as described in (ASTM-D1632, 2007). Immediately after moulding the specimens were extracted from the mould, weighted and measured (height and diameter). They were then wrapped in cling film and placed in a controlled temperature room (20ºC) for curing. Three specimens of each mixture were moulded to provide representative results.

Specimens at 28 days of curing were submitted to unconfined compression tests, according to (ASTM-D1633, 2007) and seismic waves (P and S waves) propagation times were measured with ultrasonic transducers, to evaluate the strength and stiffness of the different mixtures.

The unconfined compression tests were performed by means of an automatic load frame with displacement control and a load cell of 25 kN of capacity. Hall-Effect transducers were installed in the specimen so that strain development could be accurately measured. The wave measurements equipment includes a pair of compression transducers with 82 kHz of nominal frequency, a pair of shear transducers with nominal frequency of 100 kHz, a pulse waveform generator and data acquisition unit equipped with an amplifier connected to a personal computer with specific software to operate as an oscilloscope. The interpretation of the wave signals followed a time domain approach as suggested by (Viana da Fonseca, et al., 2009) for bender elements.

From the obtained results, two mixtures were selected to be tested in the following tests. The resistance to immersion was evaluated according to the French specification (LCPC, 2000), and the resistance to wetting and drying followed the (ABNT-NBR13554, 2012), subjecting the specimens to cycles of wetting, drying and brushing.

4 Tests Results

Unconfined compression tests and seismic wave measurements

Figure 1 shows the results of the unconfined compression strength (q) and the Young modulus (E_0) for specimens with 28 days of curing. The calculation of E_0 values was based on the elasticity theory from results of compression (P) and shear (S) wave velocities according to equation (1, 2 and 3). The wave velocities were obtained dividing the travel distance (which corresponds to the height of the specimen) by the corresponding propagation time.

$$G_0 = \rho V_S^2 \tag{1}$$

$$\nu = \frac{\left(\frac{V_P}{V_S}\right)^2 - 2}{2\left(\frac{V_P}{V_S}\right)^2 - 2} \tag{2}$$

$$E_0 = 2G_0 (1 + \nu) \tag{3}$$

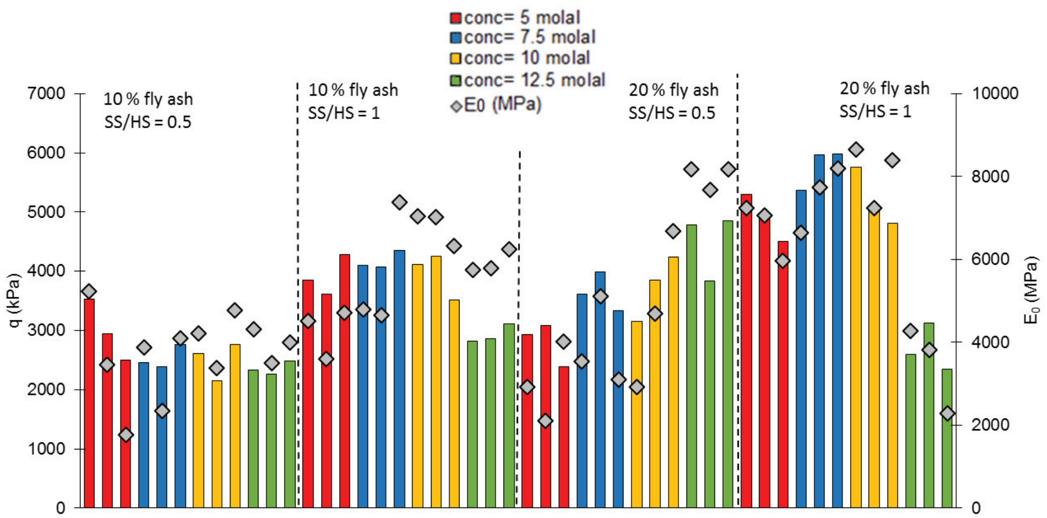

Figure 1 UCS and Young modulus results at 28 days for the 16 mixtures

Looking at the stiffness results, the E_0 values have approximately the same trend of the UCS, i. e., for specimens of the same mixture, the higher UCS result, the higher E_0, showing that strength and stiffness are related.

The graph also shows that for some mixtures the results are not very homogeneous, since the difference between the maximum and minimum values obtained in the three equal specimens was about 35 % of the average value. This was more evident in the mixtures with 5 molal of sodium hydroxide concentration, which also showed some additional fissures, as exhibited in Figure 1, indicating that possibly this concentration is not convenient for this soil.

Figure 2 Photograph of a specific part of specimen A05C5P3 surface

According to (Xu & van Deventer, 2000), mixtures with higher concentrations of sodium hydroxide should have higher strength. The present results show this trend up to the concentration 10 molal but the mixtures with 12.5 molal of SH concentration show lower values of strength. It is possible that the increased resistance with the SH concentrations (in particular with higher concentrations) might be more clear in mixtures with higher water content where the higher viscosity given by a more concentrated alkaline solution does not affect the final strength. It should be noted that the mixtures studied in this paper are compacted in the optimum point of the Modified Proctor curve of the soil mixed with fly ash and water. However, adding an alkaline solution instead of water increases the viscosity of the mixture, which might change their overall behaviour. This is an issue that requires further study.

As a consequence, avoiding the 5 and 12.5 molal concentrations, it was finally decided to select 7.5 molal concentration since it is cheaper than 10 molal. For the same reason, the mixtures with 20% of fly ash were not selected because they are more expensive; and also because they give higher strength. In fact, the option was to have two mixtures with similar cost and different strength values, although not very high, that could provide the lower bound estimate of these mixtures behaviour. In that sense, the two mixtures chosen were A05C7 and A1C7 and they were subjected to further tests to evaluate the resistance to immersion and wetting and drying. Figure 3 shows the stress-strain curves of representative tests performed on the selected mixtures, which clearly shows two different patterns of behaviour: A1C7 is stiffer achieving higher peak strength at around 0.5% of axial deformation; while A05C7 is more ductile achieving almost half of the peak strength.

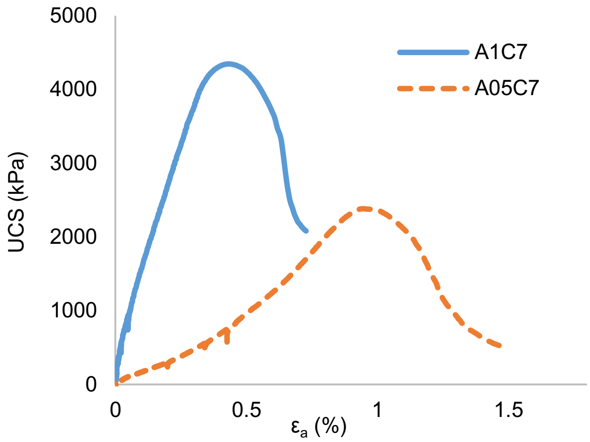

Figure 3 Stress-strain curves of the selected mixtures

Resistance to immersion and to cycles of wetting and drying

Since soil improvement with geopolymers is an innovative technique there are not standards or technical specifications to this particular material. However, the aim of this study is to use it as a replacement of a soil-cement mixture, in this case, for a low cost road. For that reason, the performance of this material according to the specification that exist for soil-cement is very important and it was thus pursued in this work.

In particular, the French specification published in the (LCPC, 2000) guide was followed due to the high experience of this country in stabilised soils with binders. This guide suggests that the short term strength should be evaluated by two different simple tests:

- Resistance at early ages, where the UCS should be higher than 1 MPa at 7 days;
- Resistance to immersion, where the ratio between the resistance to unconfined compression of a specimen with 28 days of normal curing and 32 days of immersion (R_{ci}) and a specimen with 60 days of normal curing (R_{c60}) should be higher than 0.8.

Tests were performed in specimens of mixtures A05C7 and A1C7 to address both cases and the results are presented in Table 2. The resistance at early days is evaluated based on the strength at 7 days (Rc_7). If the strength is higher than 1 MPa at 7 days, an interpolation should be done between the strength at 4 and 7 days. It is also clear that for both mixtures the resistance to immersion is satisfied.

	R_{c4} (kPa)	R_{c7} (kPa)	Age to obtain UCS = 1 MPa (Interpolation)	R_{ci} (kPa)	R_{c60} (kPa)	R_{ci}/R_{c60}
A05C7	766	1207	6 days	3319	3862	0.86
A1C7	879	1222	5 days	4948	4828	1.02

Table 2. Short term strength and resistance to immersion

On the other hand, since the aim of this material is to perform as a surface layer for a low cost road, it was important to analyse its durability in terms of resistance to wetting, drying and brushing according to the Brazilian standard (ABNT-NBR13554, 2012). For that purpose, three specimens of each mixture (A05C7 and A1C7) were moulded. The first is a control specimen, only subjected to wetting and drying cycles, and the other two were subjected to wetting, drying and brushing cycles. One cycle corresponds to 5 hours under water, 42 hours in the oven (71±2ºC) and brushing with a wire scratch brush. Between cycles, the specimens are weighted and measured (height and diameter).

The weight of all specimens decreases with time, due to the progressive loss of water during the curing process, which is related to the specificity of the geopolymeric reactions that involve loss of water during hardening. This is not compensated in the wetting phase and therefore the average retained water of the control specimen (nº 1) is negative. The volume change in the specimens is not very significant, being the average of all cycles less than 1%. The loss of mass in the other two specimens corresponds to water loss and soil loss due to brushing. However, the loss of mass corresponding to brushing is not very significant; being the maximum value obtained 1.58%.

After performing the cycles, the specimens were dried in the oven (105-110ºC) until constant mass. The specimens were tested in unconfined compression and the results are shown in Figure 4 together with the average results presented in Figure 1 for the normal curing.

The strength of the specimens from the durability tests is higher than the strength of the specimens that followed normal curing, since the geopolymeric reactions are highly accelerated with temperature increase (Sukmak, et al., 2013) (Aslani, 2015).

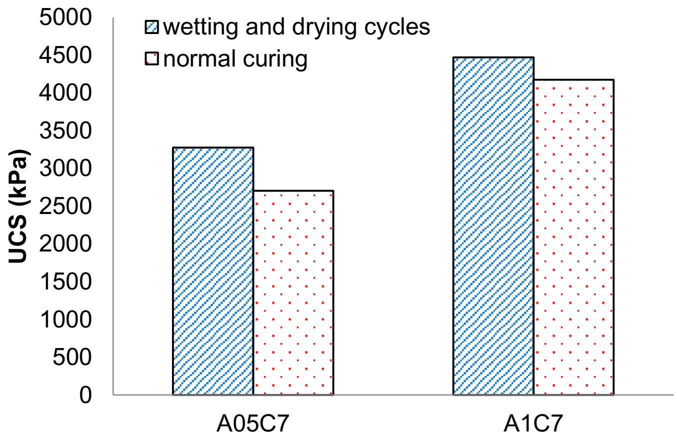

Figure 4. UCS of the specimens after durability tests

5 Conclusions

This paper presents some results of a Colombian soil stabilised with geopolymers first in terms of unconfined compression strength and elastic stiffness, and then its performance was analyse following the existing standards and specifications for soil-cement. Strength and stiffness tests were used to analyse a wide range of specimens prepared with different amounts of fly ash, soil, and alkaline solutions in distinct concentrations. From these results, two mixtures were selected which showed smaller strength values when compared with the others, but still presenting an average UCS value of 2500 kPa and 4100 kPa, for AC05C7 and A1C7 respectively.

The following tests executed in the selected mixtures comprised early strength, resistance to immersion and resistance to wetting and drying as specified in the existing standard and technical guides for soil-cement. These two mixtures showed very good results because:

- the strength was higher than 1 MPa at 7 days,
- the resistance to immersion was satisfied since the specimen cured 32 days under water after 28 days of normal curing showed approximately the same strength of the specimen that followed normal curing during 60 days;

- the wetting and drying cycles lead to higher strength values than the specimens cured in normal curing and no significant mass loss was verified due to brushing.

From these promising results, further tests should be performed in this material, such as cyclic triaxial tests, leaching tests and resistance to immersion at early ages to evaluate other properties of this material that may allow its application in unpaved roads. The possibility of using waste materials instead of Portland cement is very important to reduce the carbon footprint of soil improvement techniques and therefore should be continuously pursued.

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References

ABNT-NBR13554, 2012. Soil-cement - wetting and drying tests - Method of test. Associação Brasileira de Normas Técnicas (in Portuguese).

Aslani, F., 2015. Thermal Performance Modeling of Geopolymer Concrete. *Journal of Materials in Civil Engineering,* p. 0(0): 04015062.

ASTM-C618, 2012. ASTM C618 (2012). Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. *ASTM Int. Annu. B. Stand,* p. Vol. 04.02.

ASTM-D1632, 2007. Standard practice for making and curing soil-cement compression and flexure test specimens in the laboratory. *ASTM Int. Annu. B. Stand,* p. Vol. 04.08.

ASTM-D1633, 2007. Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders. *ASTM Int. Annu. B. Stand. ,* p. Vol. 04.08.

ASTM-D2487, 2006. Standard practice for classification of soils and engineering purposes (Unified Classification System). *ASTM Int. Annu. B. Stand,* p. Vol. 04.08.

Bernal, S., Gutiérrez, R. M., Pedraza, A. L. & Provis, J. L., 2011. Effect of binder content on the performance of alkali-activated slag concretes. *Cement and concrete research,* pp. 41: 1-8.

Davidovits, J., 1991. Geopolymers - Inorganic polymeric new materials. *Journal of Thermal Analysis ,* pp. 37(8): 1633-1656.

LCPC, 2000. Guide technique pour le traitement des sols à la chaux et/ou aux liants hydrauliques, Application à la réalisation des remblais et des couches de forme. *Laboratoire Central des Ponts et Chaussés.*

Provis, J. & Deventer, J. v., 2014. Alkali Activated Materials: State-of-the-art Report. *RILEM TC 224-AAM.*

Rios, S., Cristelo, C., Viana da Fonseca, A. & Ferreira, C., 2015. Structural Performance of Alkali Activated Soil-Ash versus Soil-Cement. *Journal of Materials in Civil Engineering,* pp. DOI: 10.1061/(ASCE)MT.1943-5533.0001398.

Sukmak, P., Horpibulsuk, S. & Shen, S. -L., 2013. Strength development in clay–fly ash geopolymer. *Construction and Building Materials,* pp. 40(0): 566-574.

Viana da Fonseca, A., Ferreira, C. & Fahey, M., 2009. A Framework Interpreting Bender Element Tests, Combining Time-Domain and Frequency-Domain Methods. *Geotechnical Testing Journal,* p. 32 (2).

Xu, H. & van Deventer, J., 2000. The geopolymerisation of alumino-silicate minerals. *International Journal of Mineral Processes,* pp. 59: 247-266..